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The Heat Budget of the Waters of a Portion of the Chesapeake Bight, 1967

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THE HEAT BUDGET OF THE WATERS OF A PORTION OF THE CHESAPEAKE BIGHT

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GLOSSARY OF TERMS

BT	Bathythermograph
c	Constant for mean height and type of clouds = .66
C	Condensation (mm)
°C	Degrees Celsius
E	Evaporation (mm)
e_a	Vapor pressure of the air at thermometer height
e_s	Saturation vapor pressure at sea surface
e_{so}	Saturation vapor pressure at 0°C
e_w	Saturation vapor pressure at sea surface temperature
H	Stored heat (g cal)
IRT	Infra-red radiation thermometer
K	A constant
°K	Degrees Kelvin
L_t	Latent heat of vaporization (cal/gm)
N	Cloud cover in tenths
P_a	Atmospheric pressure in mm of Hg.
Q	Energy flux
Q_g	Geothermal heat transfer
Q_b	Effective back radiation
Q_d	Decay of radioactive material
Q_e	Latent heat transfer
Q_h	Sensible heat transfer

GLOSSARY OF TERMS (Cont'd.)

Q_c	Heat bound or released by chemical/biological processes
Q_l	Change in stored heat
Q_m	Heat from diffusion along vertical boundaries
Q_{ob}	Effective back radiation with a clear sky
Q_p	Heat transfer due to precipitation
Q_s	Solar radiation striking the water surface
Q_t	Heat flux due to dynamic adjustments of the thermocline
Q_v	Advected heat
Q_f	Frictional dissipation due to winds and tide
r	Albedo at the sea surface (dimensionless)
RH	Relative humidity (decimal)
R	Gas constant
SHS	Shelf hydrographic survey
t	Time
T	Temperature (°C or °K)
T_d	Temperature (°C) of dry bulb thermometer
T_s	Temperature (°C) of sea surface
T_z	Temperature (°C) at depth z
V	Wind speed (knots)
Z	Depth (m)
ρ	Density (g/cm^3)

ABSTRACT

Of the significant terms in the heat budget of an oceanic volume, insolation and heat content of the water were measured while evaporation, sensible heat transfer, effective back radiation and reflected radiation were computed using empirical formulae and standard meteorological data. Advection of thermal energy was found by solving the heat budget equation.

The heat budget of the study area, 5000 km^2 in extent and located on the continental shelf east of the Chesapeake Bight, was computed for approximately monthly intervals during 1967. The accuracy of the analysis was investigated and, where possible, the magnitude of errors was determined.

Advection of thermal energy was found to be in qualitative agreement with known current patterns. A correlation of advected heat with winds and temperature patterns, however, was not apparent.

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I INTRODUCTION

Over a period of several years, there exists a balance between the quantity of radiant energy absorbed and emitted through the outer boundary of the earth's atmosphere. Since the mean temperature of the earth does not change appreciably on a multiannual basis, the law of energy conservation requires that total energy inputs must equal total outputs. This working hypothesis can be applied to a small portion of either the lithosphere, hydrosphere, or atmosphere, for one year or less if all sources, sinks and methods of storing energy affecting the region under study are included. Care must also be taken to include the various mechanisms acting to convert energy from one form to another (i.e., the frictional conversion of kinetic energy to heat or the metabolic conversion of chemically stored energy to heat). If the quantity of energy added to, removed from, and stored within a small portion of the earth's hydrosphere can be determined at monthly intervals, an energy budget can be established. Monthly changes in the various components of the energy budget can be used to determine the importance of physical phenomena responsible for these changes. When thermal energy is investigated, the study is called a heat budget study.

A general heat budget requires a balance between the net heat into a system (heat in minus heat out), the changes in internal heat (due to dynamic adjustments within the system as well as heat consumed or released through physical or chemical processes) and the quantity of heat stored in the system (the temperature of the medium under study).

When computing a heat budget, it is most convenient to measure energy fluxes (the amount of energy passing through a unit area during a given period of time). With Q designating energy fluxes, the general heat budget equation can be written:

$$(Q_{in} - Q_{out}) \text{ horizontal boundaries} + (Q_{in} - Q_{out}) \text{ vertical boundaries} + \Delta Q \text{ internal} = \Delta \text{ stored heat} \quad \text{(Neumann and Pierson, 1966)} \qquad (1.1)$$

A more detailed expression of equation (1.1) for an oceanic region is:

$$Q_s - r\,Q_s \pm Q_h \pm Q_e - Q_b \pm Q_v \pm Q_t \pm Q_m \pm Q_c \pm Q_f \pm Q_d \pm Q_g \pm Q_p = Q_l \qquad (1.2)$$

where: + indicates a heat source term

- indicates a heat sink term

± indicates either source or sink

r is albedo at the water surface

the subscripts represent sources or sinks due to the following:

s - solar radiation striking the water surface

h - sensible heat transfer

e - latent heat transfer

b - back radiation from the sea surface

v - advected heat

t - dynamic adjustments of the thermocline

m - diffusion along vertical boundaries

c - chemical-biological processes

f - frictional dissipation due to winds and tide

d - decay of radioactive material

g - geothermal heat transfer

p - precipitation on the water surface

and Q_1 is a measure of the change in stored heat as determined by water temperature changes. (A glossary of all terms used can be found on page vii).

Budyko (1956) and Laevastu (1960) have published reviews of previous heat budget work and present empirical formulae for computing the individual terms. These equations have been applied to the present heat budget investigations.

The objective of this study was to establish the magnitude of various heat budget terms given in equation (1.2) and investigate the accuracy of these values. In computing the heat budget, stored heat was determined from water temperature measurements while the combined effects of advection, lateral diffusion and dynamic adjustments of the water column were obtained by solving equation (1.2).

II DESCRIPTION OF AREA AND DATA

The area under study, located in the central Chesapeake Bight and depicted in Figure 1, covers approximately 5000 km^2 of the continental shelf. It is bounded on the west by the Virginia coast and the mouth of the Chesapeake Bay, on the east by 74°57.5'W. longitude, on the north by 37°10' N. latitude, and on the south by 36°40' N. latitude.

Water depths in this area vary from zero at the coast to a maximum of 44 m in the northeast corner, with a mean depth of 22 m. The volume of water in the region at mean low water is $1.1 \times 10^{11} m^3$.

Temperature data for computing the stored heat were gathered during oceanographic cruises conducted by personnel of the Virginia Institute of Marine Science as part of a Shelf Hydrographic Survey program. Cruises were made approximately each month (Table 1) with stations spaced at 18.5 kilometer intervals as shown in Figure 1. Vessels used were the trawler Sea Breeze and the USNS Range Recoverer. Temperatures were measured with a bathythermograph (BT) with the surface temperature of the BT trace corrected to agree with those measured by thermistor probe. Drift bottles and sea bed drifters were released at all stations and surface to bottom salinity samples were collected periodically.

Data on wind velocity, sea surface temperature, wet and dry bulb temperatures, cloud cover, and barometric pressure were obtained from Chesapeake Light Tower at 36°54' N. latitude and 75°43' W. longitude.

TABLE 1

Dates of Shelf Hydrographic Survey Cruises (1967)

Cruise Designation	Number of Stations sampled	Dates of Cruises
SH01	16	19-21 Feb.
SH02	18	18-21 Mar.
SH03	21	20-23 Apr.
SH04	21	16-19 May
SH05	21	21-24 June
SH06	21	17-20 July
SH07	21	16-20 Aug.
SH08	21	26 Sept.-3 Oct.
SH10	21	16-19 Nov.
SH11	7	15-17 Dec.

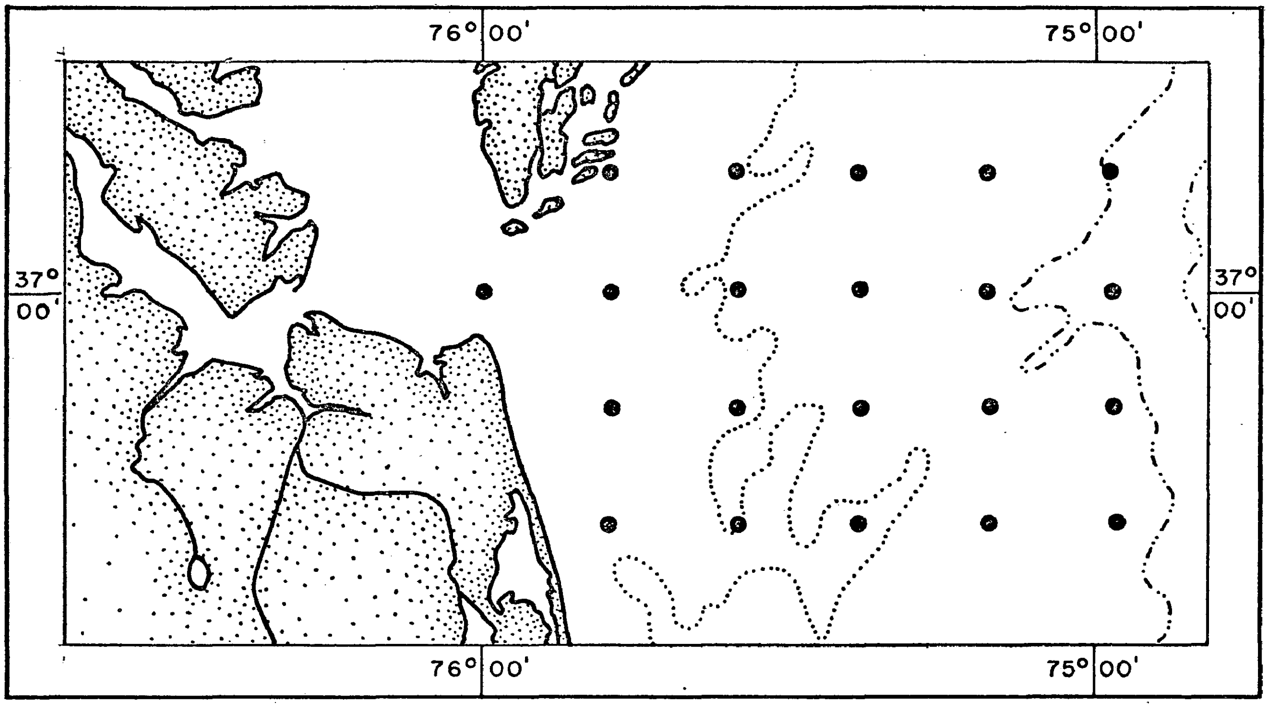

Figure 1. A representation of the study area showing station locations.

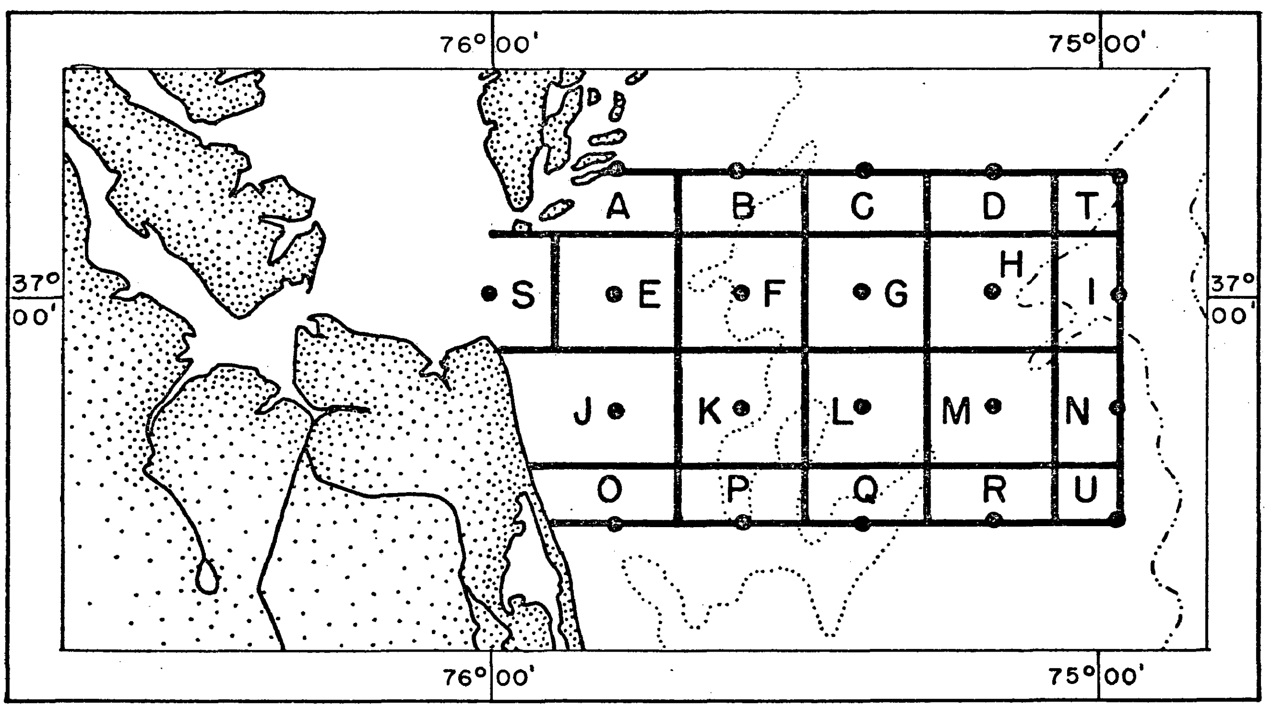

Figure 2. Sub-areas for computing heat content of the water.

Insolation data were obtained from Cape Hatteras, North Carolina, and precipitation measurements from Norfolk, Virginia.

III ANALYSIS OF HEAT BUDGET TERMS

The terms given in equation (1.2) can be grouped into three general categories.

Negligible Heat Flux Terms: The ninth through the thirteenth terms on the left hand side of equation (1.2) are considered negligible. As summarized in Table 2 and discussed below, the largest of these contributes or removes a quantity of thermal energy which is less than 2.5 percent of the solar radiation contribution to the system.

Motion Induced Heat Flux Terms: Heat fluxes due to dynamic adjustments of the thermocline (Q_t) and diffusion through vertical boundaries (Q_m) will be included in the advected heat flux term (Q_v) since neither direct measurements or sufficient data to make estimates of Q_t and Q_m could be obtained.

Major Heat Flux Terms: Values of the remaining terms in equation (1.2) can either be measured directly, as in the case of Q_s and Q_l, or computed from available data. They reflect the effects of the physical phenomena which play a major role in changing the thermal energy content of the region under study.

TABLE 2

Estimated values of negligible heat flux terms

Heat term	Value	Source
Q_p (precipitation)	1125 cal/cm^2 yr	Greer
Q_g (geothermal heat flux)	57 cal/cm^2 yr	Menard (1964)
Q_d (radioactivity)	4 x 10^{-3} cal/cm^2 min	Defant (1961)
Q_f (kinetic energy)	.01% of Q_s	Defant (1961)
Q_c (chemical processes)	235 cal/cm^2 yr	Laevastu (1960)

Negligible Heat Flux Terms

Q_p - Precipitation. To determine the amount of energy contributed by precipitation, U. S. Weather Bureau data from Norfolk, Virginia, were used (ESSA, 1967). A total accumulation of 1148 mm of precipitation was recorded in Norfolk, Virginia, during 1967. Assuming an average temperature of 10°C for this precipitation, 1125 cal/cm^2 yr would have been added to the water. This is only about .8% of Q_s which was 138,000 cal/cm^2 yr and is considered negligible. An average temperature of precipitation of 20°C as used by Jung (1953) would have contributed 1.6% of Q_s; however, a figure of 10°C is considered more realistic for the study area.

Snow fell during December, January, and February, with the largest amount in February when the snowfall was equivalent to a depth of 20.6 mm of rain. Assuming a latent heat fusion of 79.71 calories per gram and a density of 1 g/cm^3, the energy given up by the water in melting the snow was 164 cal/cm^2. This is only 2.15% of Q_s (7653 cal/cm^2 during February) and is considered negligible.

Q_f - Heat flux from frictional dissipation of energy. Kinetic energy of waves and tides is partially converted to thermal energy through friction. The heat contributed by the dissipation of wave energy is only .01% of Q_s (Defant, 1961) and need not be considered in the heat budget. An estimate for conversion of tidal energy to heat was given by Defant as 41.9 cal/cm^2 yr for the continental shelf. This is only .1% of Q_s in the present study.

Q_c - Heat from chemical reactions. Heat can be bound or released by chemical processes, the most important of which is photosynthesis.

Such energy, computed by Laevastu (1960) to be 235 cal/cm^2 yr, is only .2% of Q_s in this study and need not be further considered.

Q_g - Geothermal heat flux. Heat flux through the sea floor is small except in "hot" areas such as the mid-Atlantic Ridge. Using an average heat flow for the continents and oceans combined as given by Menard (1964), 57 cal/cm^2 yr is contributed by this source. Menard further states that the heat flow over the continental shelves is less than that given above. In any case, the energy flow through the sea floor can be considered negligible with respect to Q_s.

Q_d - Radioactivity. The heat from radioactive disintegration in sea water is negligible according to Defant (1961).

Major Heat Flux Terms

After deleting the negligible heat flux terms and including Q_m and Q_t in Q_v, equation (1.2) becomes:

$$Q_s - rQ_s \pm Q_e \pm Q_v - Q_b \pm Q_h = Q_1 \qquad (3.1)$$

Q_s - Insolation. Only a portion of the solar radiation incident on our atmosphere reaches the earth's surface. The amount of this radiation actually received on a level surface is called insolation and can be measured with a pyranometer (Byers, 1959).

Insolation measurements used in this study were taken at Cape Hatteras, North Carolina; although Cape Hatteras lies 150 kilometers south of the study area, the difference in latitude can account for only a 1-2% difference in Q_s. Moreover, the average daytime cloud cover at Cape Hatteras was found to be almost identical to that in the study area in 1967. The few gaps in the data were filled using adjusted Charleston, South Carolina, insolation.

Daily values were summed and multiplied by the area of water surface to calculate the total insolation for periods between cruises. Time was reckoned from the mid-time of one cruise to the mid-time of the next. Mean daily values of Q_s are given in Table 3.

The computation of Q_s from pyranometer records is not exact. "Nicolet (1948) has stated that in a continuous record of the global radiation of sun and sky, an accuracy of $\pm$ 5% in the short term integrated totals represents the result of good and careful work" (WMO Pub. No. 8, 1956).

rQ_s - Reflected ratiation. Radiation incident on the water surface is not entirely absorbed; some is returned to the atmosphere depending on the albedo at the water surface. Albedo (defined as "a measure of the part of the incoming solar radiation which is reflected" - Petterssen, 1958) is a function of solar altitude, the relative amounts of direct and diffuse radiation, and the sea state. Budyko (1956) gives mean values of albedo for water surfaces for each month as a function of latitude. The values were obtained from both experimental and theoretical work based on means of sea state, solar altitude, and ratiation types. Since a breakdown of radiation into direct and diffuse components was not available for the present study, a more sophisticated computation of albedo was not attempted.

The values of albedo (r) interpolated for 37° latitude from data of Budyko are given in Table 4. Reflected radiation (rQ_s), the product of albedo and solar insolation, is given in Table 3.

Reflected ratiation is a linear function of Q_s and is subject to the same 5% error. In addition, Budyko's values for albedo are not

TABLE 3

Values of measured and computed heat budget terms.

Values given are mean daily energy fluxes for the periods indicated.

calories/day x 10^{13}

Period	Q_s	rQ_s	Q_e	Q_h	Q_l	Q_b	Q_v
I/I-II/20	1049	-102	-414	- 96		-731	
II/21-III/19	2021	-162	-381	- 82	- 26	-809	- 613
III/20-IV/21	2502	-176	- 77	248	279	-756	-1462
IV/22-V/17	2387	-149	-244	252	1338	-667	- 241
V/18-VI/22	2551	-153	-347	- 3	1056	-678	- 314
VI/23-VII/18	2306	-138	-281	41	962	-553	- 413
VII/19-VIII/18	2361	-142	-350	- 16	387	-556	- 910
VIII/19-IX/29	1963	-127	-976	-151	95	-641	27
IX/30-XI/17	1783	-150	-1342	-466	-1184	-755	- 254
XI/18-XII/16	1074	-114	-602	-298	-1103	-691	- 472
XII/17-XII/31	965	-107	-720	-352	-1400	-712	- 474

TABLE 4

Albedo at the sea surface for latitude 37° N.

Interpolated from Budyko (1956).

Month	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Albedo(r)	.104	.087	.077	.067	.060	.060	.060	.060	.067	.077	.101	.111

exact. These values are in good agreement with those of other scientists, and the resultant error from this source is probably small.

Q_e - Latent heat flux. When there is a vertical moisture gradient, diffusion of water vapor occurs. This flux, largely effected by turbulent air motion, is directly proportional to the strength of the water vapor gradient and can be expressed by an equation of the form:

$$E = - K(e_w - e_a) V \tag{3.2}$$

Laevastu (1960) has formulated the following equation based on the work of Rohwer (1931). When the water vapor gradient is positive ($e_w > e_a$),

$$E = \text{Evaporation rate} = (.26 + .0385 V) (.98 e_w - e_a) \frac{\text{mm}}{24 \text{ hrs.}} \tag{3.3}$$

(V is wind velocity in knots).

When the vertical humidity gradient is negative, condensation takes place according to the formula:

$$C = \text{Condensation} = (.0385 V) (e_w - e_a) \frac{\text{mm}}{24 \text{ hrs.}} \tag{3.4}$$

It is assumed that the air just above the surface is saturated with water vapor and at the same temperature as the surface water.

Wind speeds used in this study were measured at an anemometer height of 39 m and the wet and dry bulb air temperatures at 18 m. While these are not the standard heights for such observations, Roll (1965) states that the variations of these measured parameters is proportional to the logarithm of height above the sea surface, and so variations in measurement over the above height ranges should be small.

To determine the heat flux resulting from evaporation or condensation, the values of E or C were multiplied by the product of the density of water (taken as 1 g/cm^3) and the latent heat of vaporization for salt water, which is given by Jacobs (1951) as:

$$L_t = (594.9 - .51\ T_s)\ \text{cal/g} \qquad (3.5$$

Q_e was computed for each of four daily weather observations taken at Chesapeake Light Tower and summed to get the total for the day. These daily figures were in turn summed to find Q_e for the periods between successive oceanographic cruises. Mean daily values presented in Table 3 were obtained by dividing by the number of days in the period.

Latent heat exchange is a non-linear function of sea surface temperature (T_s), air temperature (T_d), relative humidity (RH), and wind velocity (V). Because some of these appear more than once in the equation, there is a possibility of compensating or compounding errors. In order to determine the accuracy of Q_e, the accuracy of the variables was first analyzed and set as:

$$T_s\ (^\circ C) = T_s \pm\ .28$$

$$T_d\ (^\circ C) = T_d \pm\ .05$$

$$RH = RH \pm\ .02$$

$$V\ (\text{knots}) = V \pm .5$$

A computer program was written to calculate Q_e and the maximum and minimum values of this quantity within the above limits (Appendix A). These values are given in Table 5.

Q_h - Sensible heat flux. Early work by Bowen in 1926 assumed that the "Austauch" for heat and water vapor are equal. Based on this principle, Laevastu developed the following formula for sensible heat transfer:

$$Q_h = 38.9(.264+.0385V)(T_s-T_d)(Pa/1000)\ \text{cal/cm}^2\ 24\ \text{hrs.} \qquad (3.6)$$

(where V is wind velocity in knots).

TABLE 5

Maximum, "no error," and minimum values of Q_e, Q_h, and Q_b (cal x 10^{13}/day).

Period	Qty	Min	$-\Delta$	No Error	$+\Delta$	Max	% Error = $\left(\frac{+\Delta \times 100}{\Sigma \text{No error}}\right)$
I/1-II/20	Q_e	319	95	414	106	520	
	Q_h	37	59	96	61	157	
	Q_b	703	28	731	54	785	
	Total	1059	182	1241	221	1462	17.8%
II/21-III/19	Q_e	281	100	381	109	490	
	Q_h	18	64	82	64	146	
	Q_b	773	36	809	48	857	
	Total	1072	200	1272	221	1493	17.4%
III/20-IV/21	Q_e	19	58	77	98	175	
	Q_h	-296	48	-248	48	-200	
	Q_b	717	39	756	52	808	
	Total	440	145	585	198	783	33.8%
IV/22-V/17	Q_e	117	127	244	137	381	
	Q_h	-302	50	-252	50	-202	
	Q_b	626	41	667	60	727	
	Total	441	218	659	247	906	37.5%
V/18-VI/22	Q_e	215	132	347	143	490	
	Q_h	-38	41	3	41	44	
	Q_b	641	37	678	49	727	
	Total	818	210	1028	233	1261	22.7%
VI/23-VII/18	Q_e	134	147	281	176	457	
	Q_h	-74	33	-41	35	-6	
	Q_b	507	46	553	56	609	
	Total	567	226	793	267	1060	33.7%
VII/19-VIII/18	Q_e	188	162	350	184	534	
	Q_h	-12	28	16	29	45	
	Q_b	511	45	556	54	610	
	Total	687	235	922	267	1189	29.0%
VIII/19-IX/29	Q_e	785	191	976	215	1191	
	Q_h	110	41	151	43	194	
	Q_b	596	45	641	49	690	
	Total	1491	277	1768	307	2075	17.4%

TABLE 5 (Cont'd.)

Maximum, "no error," and minimum values of Q_e, Q_h, and Q_b (cal x 10^{13}/day).

Period	Qty	Min	$-\Delta$	No Error	$+\Delta$	Max	% Error = $\left(\frac{+\Delta \times 100}{\Sigma \text{No error}}\right)$
IX/30-XI/17	Q_e	1180	162	1342	180	1522	
	Q_h	413	53	466	55	521	
	Q_b	714	41	755	46	801	
	Total	2307	256	2563	281	2844	11.0%
XI/18-XII/16	Q_e	508	94	602	112	724	
	Q_h	245	53	298	54	352	
	Q_b	659	32	691	51	742	
		1412	179	1591	227	1818	14.3%
XII/17-XII/31	Q_e	611	109	720	115	835	
	Q_h	295	57	352	58	410	
	Q_b	674	38	712	58	770	
	Total	1580	204	1784	231	2015	12.9%

This formula is to be used when the water is warmer than the air. As in the case of Q_e, a different formula is necessary when the thermal gradient is reversed. In the event that the overlying air is warmer than the water surface, sensible heat will be directed into the water according to the equation:

$$Q_h = 1.5V(T_s - T_d)\ Pa/1000 \quad cal/cm^2\ 24\ hrs. \qquad (3.7)$$

In both equations, (3.7) and (3.6), it is assumed that the air immediately adjacent to the water surface is at the temperature of the water.

Sensible heat transfer was computed as above and multiplied by the surface area to get total Q_h. As with the other parameters it was estimated four times a day and the mean daily Q_h values were calculated for periods between cruises.

Sensible heat transfer is a function of wind velocity (V), sea surface temperature (T_s) and air temperature (T_d). These parameters are known to an accuracy of $\pm.5$ knots, $\pm.28°C$, and $\pm.05°C$ respectively. Using the same procedure as described for determination of Q_e, the maximum, minimum, and "no error" values of mean daily Q_h were computed and are shown in Table 5.

Q_b - <u>Heat flux due to effective back radiation</u>. The sea surface emits long wave radiation proportional to the fourth power of temperature in accordance with the Stefan-Boltzman law (McLellan, 1965).

In addition to this long wave emission from the sea, there is long wave emission from the atmosphere, mainly from water vapor. The difference between the outgoing and incoming long wave radiation is known as "effective back radiation" and can be calculated from meteorological and oceanographic observations as shown by Laevastu (1960) who gave the following equation for effective back radiation with a clear sky (Q_{ob}):

$$Q_{ob} = \frac{14.38-.09T\ -4.6\ RH}{69.72} \quad \frac{cal}{cm^2\ min} \tag{3.8}$$

(where RH here is expressed as a decimal).

The influence of clouds on effective back radiation is appreciable and Budyko (1956) gives the correction:

$$Q_b = Q_{ob}\ (1 - cN^2) \tag{3.9}$$

where N is cloud cover in tenths and the factor "c" is a correction for the mean height and type of clouds (interpolated from Budyko's tables to be .66 for latitude 37 N). Since available weather information did not include type and height of clouds, this constant must serve as a best approximation.

The cloud cover information from Chesapeake Light Tower was in eighths of the sky covered instead of the more usual tenths and a correction of 1/.64 is required in equation (3.9). Converting from cal/cm²min to cal/cm² 6 hr and multiplying by the surface area gives:

$$Q_b = \frac{(1-1.03125\ N^2)\ (14.38\ \ -.09\ T_s\ -4.6\ RH) x 360 x 5007 x 10^{13}}{69.72} \quad \frac{cal}{6\ hrs} \tag{3.10}$$

Mean daily values of Q_b for the different periods are given in Table 3.

Effective back radiation is dependent on sea surface temperature (T_s), relative humidity (RH), and cloud cover (N). The accuracy of T_s and RH are as shown for Q_e and Q_h; the cloud cover is accurate to .5 eighths. The computed maximum, minimum, and "no error" values of Q_b are given in Table 5.

Q_1 - Change in stored heat. Pattullo, et al. (1969) computed the heat content of the water off the coast of Oregon using an equation of the form:

$$H = \sum_{o}^{z} \rho\ Cp\ \ T\ \Delta Z \tag{3.11}$$

where T represents the mean temperature in the water layer of thickness ΔZ. They found that the product ρCp was nearly constant, and were thus able to ignore changes in water density due to salinity and temperature distribution. The study was limited to the upper hundred meters of the water because of the scarcity of temperature information below this level.

In computing the change in stored heat, it is proper to reckon the heat content from a level below which there is no change in temperature with time. This method was used by Jung (1953) who calculated the change in stored heat by plotting successive bathythermograph traces on a single sheet of paper and measuring the difference in stored heat by planimetry.

In this study, the water is sufficiently shallow that all stations reflected an appreciable change in bottom temperature over a one month interval. Since bathythermograph data were available to the bottom, the heat content of the entire water column was considered.

For computing stored heat (H), the study area was divided into sub-regions centered on BT stations as shown in Figure 2. The mean depth in each of these sub-areas was calculated by taking the average of all the depths within the square as shown on U. S. Coast and Geodetic Survey charts 1109 and 1222. These mean depths, at mean low water, are given in Table 6.

TABLE 6

Mean depths and areas of sub-areas.

Sub-area designation	mean depth (m)	area ($cm^2 x 10^{11}$)
A	6.12	22.66
B	17.63	17.17
C	25.73	17.17
D	32.16	17.17
E	11.82	34.34
F	19.42	34.34
G	26.54	34.34
H	34.44	34.34
I	37.82	17.17
J	13.51	46.02
K	19.04	34.34
L	22.96	34.34
M	29.22	34.34
N	32.68	17.17
O	14.00	19.92
P	18.47	17.17
Q	21.43	17.17
R	27.98	17.17
S	7.95	17.17
T	37.36	8.585
U	27.61	8.585

Stored heat (H) was computed for each of the sub-areas and summed to obtain H for the total volume. Temperatures were read from the BT trace at 3 meter intervals and the mean temperature in each 3 meter layer was calculated using the formula:

$$T = \frac{1}{2}\left(T_z + T_{(z + \Delta z)}\right) \qquad (3.12)$$

When the mean depth in the sub-area was less than the depth shown by bathythermograph, the BT trace was truncated at this mean depth. The temperatures at BT stations were assumed representative of the sub-areas.

As a check on the accuracy of calculating heat using 3 meter depth increments, another method was tried by which inflection points in the BT trace were plotted and the heat content determined by summing over contained intervals. The results of the two methods were almost identical. The horizontal integration method of computing stored heat was also tried. In this case the heat content of the water between successive depth contours was computed. Once summed, this yielded results which were within 0.2% of those computed by the vertical integration method.

In addition to computing total stored heat, the heat content was broken down into the amounts above and below the thermocline. There was a strong thermocline only during the warmer months of May, June, July, and August, and the values for these months are given in Table 7. In computing these values, the bottom of the thermocline (taken as the level below which the thermal gradient became less than .27°C/meter) served as the dividing line. At shallow stations where the water was nearly isothermal, the total water column was included in the portion above the thermocline.

TABLE 7

Stored heat (H) above and below the thermocline (total for all stations).

Total Heat	SH 4 (17 May) 11.8×10^{17} cal	SH 5 (22 Jun) 15.6×10^{17} cal	SH 6 (18 Jul) 18.1×10^{17} cal	SH 7 (18 Aug) 19.3×10^{17} cal
H above T.C.*	8.6×10^{17} cal	9.8×10^{17} cal	14.3×10^{17} cal	16.6×10^{17} cal
H below T.C.	3.2×10^{17} cal	5.8×10^{17} cal	3.8×10^{17} cal	2.7×10^{17} cal
Depth of T.C.	14.78 m	11.95 m	15.25 m	17.2 m
Total Depth	22 m	22 m	22 m	22 m
% water above T.C.	67%	54%	69%	78%
% water below T.C.	33%	46%	31%	22%
mean T (°C) upper layer	11.9°C	16.6°C	19.1°C	19.2°C
mean T (°C) lower layer	9.0°C	10.6°C	11.5°C	11.5°C
mean T (°C) total	10.9°C	14.4°C	16.8°C	17.9°C

*Thermocline

The density (ρ) and the specific heat at constant pressure (Cp) changed slightly with temperature, salinity, and depth, but the product ρCp remained essentially constant in the ranges encountered. (Salinity: 25 to 35 ‰ temperature: 4 to 25°C, and depth: 0 to 44 m). Cox and Smith (Neumann and Pierson, 1966) studied the changes of Cp and show that within the ranges encountered in this study, Cp increases with increasing temperature, and decreases with increasing salinity while the effect of depth is negligible. The density of sea water (ρ) increases with salinity and depth, but decreases with temperature. The net result of these changes is that the product ρCp varies from .9771 cal/cm^3°C, (at 25°C, 35 ‰) to .9853 cal/cm^3°C (at 4°C, 25 ‰). The value of the product used here was .98 cal/cm^3°C.

After computing the mean daily stored heat (H) for each cruise, the change in stored heat with respect to time was determined by:

$$Q_1 = (H_{(t + \Delta t)} - H_t) \qquad (3.12)$$

where t represents time. Values of H are given in Table 8 and those of Q_1 in Table 3.

For the Shelf Hydrographic Survey cruises of February and March (SH01 and SH02) there was no BT information for certain of the stations. To fill in the gaps, charts of sea surface temperature from IRT (Infra-red Radiation Thermometer) overflights by the Sandy Hook Marine Laboratory (1967) were used. Surface isotherms from the IRT charts were transcribed to plots of T_s from the SHS cruises and the missing temperatures were assumed to follow the trend of the nearest BT station.

During the December cruise (SH11) only 7 of the 21 stations were occupied. Rather than discard the data, total heat was calculated as follows:

TABLE 8

Stored heat (H) in cal x 10^{17}

Cruise No. and Date (1967)			
SH	1	19-21 Feb.	7.47×10^{17} cal
SH	2	18-21 Mar.	7.40 "
SH	3	20-23 Apr.	8.32 "
SH	4	16-19 May	11.8 "
SH	5	21-24 Jun.	15.6 "
SH	6	17-20 Jul.	18.1 "
SH	7	16-20 Aug.	19.3 "
SH	8	26 Sept.-3 Oct.	19.7 "
SH	10	16-19 Nov.	13.9 "
SH	11	15-17 Dec.	10.7 "
		31 Dec. (estimated)	8.6 "

Seven BT stations were occupied on the December cruise. During the November, 1967, and January, 1968, cruises (SH10 and SH01) these same stations accounted for 32.68% and 31.78% of the stored heat respectively, or an average of 32.23%. The stored heat of the seven December (SH11) stations was calculated and divided by .3223 to obtain the total heat for the area. This stored heat was determined to be 10.9×10^{17} cal.

To verify this figure, stored heat was also calculated by the following method:

During January of 1968 (SH01), fifteen stations were sampled for temperature. These accounted for heat of 5.39×10^{17} cal. These same stations had accounted for 83.45% of the total heat of 13.9×10^{17} during November, 1967 (SH10). Based on this information, total heat for the January, 1968, cruise was calculated as $5.39 \times 10^{17}/.8345$ or 6.46×10^{17} cal. The values for November and January were plotted on graph paper and the value of stored heat for SH11 was interpolated as 10.38×10^{17} cal. A value for 31 December was likewise interpolated.

The average of the two results for the December, 1967, cruise (SH11) is 10.7×10^{17} cal, which is the value used here. While the above method appears to give good results in the winter when the water is isothermal, it is not recommended for summer or other periods when a strong thermocline exists.

The change in stored heat is probably the least accurate of the heat budget terms. It was obtained by subtracting the quantity of stored heat (H) for one cruise from that of the previous cruise. The individual values of H are very large and are subject to appreciable error.

The computation of Q_1 assumes the following:

1) Synopticity of bathythermograph observations
2) Homogeneity of temperature in sub-areas
3) No errors in station keeping (navigation)
4) 100% accuracy of the PTI thermometer
5) 100% accuracy of BT depth sensor
6) 100% precision of BT temperature sensor
7) Legitimacy of interpolating/extrapolating BT data to mean sub-area depths
8) Legitimacy of using IRT data to fill in missing BT station data
9) Exact integration of TdZ and 100% accuracy of the vertical integration method
10) Constancy of the product ρCp
11) Exact knowledge of the mean value of Q_1 in sub-areas.

None of these assumptions is completely valid. The BT data were only approximately synoptic since cruises were at least two days in duration. It is evident from these data that this interval is sufficient for a considerable change in temperature, especially at the inshore stations.

Plots of surface isotherms from IRT overflights clearly indicate the heterogeneity of the water in the study area. The size of sub-areas is relatively small, however, and the temperature variation on this scale is not so apparent.

Navigation accuracy is about $\pm$ 1 mile and the variation of BT indicated depths from cruise to cruise reveals errors in station keeping. The PTI is accurate to $\pm$ 0.01°C and the error from this source is negligible. Precision of the BT is only 0.5°C, however, and this coupled with depth accuracy of only 1 m could cause appreciable error in stored heat calculations.

The product of density and specific heat (ρCp) varies slightly with temperature and salinity. The maximum variation in this product is only .8%, however, and this is so much smaller than other sources of error that it is not considered significant.

The other assumptions are also questionable to one degree or another, but a quantitative assessment of their error is not possible from available data.

Q_v - Advected heat. Advection of heat was found by solving the heat budget equation:

$$Q_v = -(Q_s - rQ_s \pm Q_e \pm Q_h - Q_b - Q_l)$$

A positive value for advection indicates that heat was advected into the study area while a negative value indicates heat was removed by advection. The daily mean values of Q_v are shown in Table 3.

Advection in the study area is from two sources: the primary source is movement of continental shelf water, and a secondary input of water from the Chesapeake Bay. In order to determine the relative amounts of energy contributed by the two sources, a detailed knowledge of currents and water temperature would be required. It is assumed that there is a two layered circulation pattern at the Bay mouth (Pritchard, 1955) which could account for appreciably more current outflow than that contributed by fresh water runoff into the Bay. Even if the outflow was known, detailed knowledge of where the water went once it left the Bay would still be required. While it is known that the water generally moves south after exiting the Bay the actual course is highly variable (Norcross and Harrison, 1967).

It is important to understand that advection solved for in this study is net advection. Realizing that patterns of shelf water movement can change often, the gross advection of heat must be larger. Because of this and the lack of temperature data for advected water, it is impossible to determine actual current velocities from Q_V.

Wind induced water movement is important to continental shelf advection, and resultant wind vectors, calculated using an IBM 1130 computer program, are given in Table 9. Two sets of values are shown, one for all winds and another for winds greater than twelve knots. Munk (1947) reported that twelve knots can be considered a critical wind speed, above which there is a "jump" in the frictional drag. Doebler (1966) found no evidence of this critical wind speed, however, and there is disagreement on the subject.

Due to the method of computing Q_V, it necessarily contains the residual errors from all of the other terms. A quantitative assessment of this total error in Q_V is not possible from available information, but the negative values of Q_V are in general agreement with actual drift patterns in the area. It is emphasized, however, that the drift is highly variable as shown by Norcross and Stanley (1964) and Bumpus (1969).

TABLE 9

Resultant Wind Vectors (Direction toward which wind is blowing and displacement in nautical miles).

Period	All Winds		Winds > 12 knots	
	DIRECTION	DISPLACEMENT	DIRECTION	DISPLACEMENT
I/1-II/20	088°	607 N. Miles	092°	578 N. Miles
II/21-III/19	089°	471	083°	527
III/20-IV/21	163°	68	121°	170
IV/22-V/17	043°	280	66°	316
V/18-VI/22	238°	632	208°	437
VI/23-VII/18	319°	323	318°	101
VII/19-VIII/18	317°	122	197°	40
VIII/19-IX/29	225°	441	201°	450
IX/30-X/17	207°	284	199°	243
X/18-XI/17	118°	363	102°	254
XI/18-XII/16	117°	302	115°	292
XII/17-XII/31	136°	264	128°	263

IV SUMMARY

For the year 1967, rQ_s averaged 7% of Q_s; while Q_e, Q_b, and Q_h were 30%, 36%, and 10% of Q_s, respectively. All of these values were negative (-) for every period except Q_h, which was positive (+) in the late spring and early summer. Reflected radiation was relatively constant throughout the year, as was effective back radiation. Q_e and Q_h varied considerably, however, with both terms being largest in the fall and early winter. Solar insolation varied only 10% from the average for March through September, but decreased considerably during the winter. Stored heat changed rapidly during the period of vernal warming as well as in the late fall, consistent with the pattern shown by Bigelow (1933) and others. Advection was strongest in April and August, but was highly variable throughout the year and exhibited no apparent trend.

While there was no measurement of stored heat on 1 January 1967, the sea surface temperature at Chesapeake Light Tower was 6.7°C on that date. A year later, on 31 December 1967, the sea surface temperature was 7.2°C, which is an indication that the temperature may have made a complete cycle during the year.

The advection computed in this study is in good qualitative agreement with observations. Bigelow (1933) and others have established the general temperature distribution in the continental shelf waters and, as expected, have found cooler water to the north. Hence, a negative value of Q_v suggests southerly moving currents as found by Norcross and Stanley (1967) and Bumpus (1969).

The only period for which Q_v was positive was in August and September, and then only slightly so. Hurricane Doria passed through the study area during this period and this anomaly, compounded by the loss of meteorological information when the hurricane forced evacuation of Chesapeake Light Tower, could have caused the increase in Q_v. Miller (1952) found evidence of a cyclonic eddy near Cape Charles (Lat. 37° 07' N, Long. 75°58' W), as did Bumpus (1969).

The density discontinuity at the thermocline suggests a two-layered circulation pattern where current velocities in the upper and lower layers are different (Neumann and Pierson, 1966). Norcross and Stanley (1967) observed this pattern in the study area, but a quantitative assessment is not possible from available temperature information.

Error values for Q_e, Q_h, and Q_b were relatively constant throughout the year; however, the percentage errors (which depend on the values of the terms themselves as well as the size of errors) varied from 11% to 37.5% with peaks in April and July. Q_s and rQ_s are subject to 5% error throughout the year, while the error in Q_l and Q_v was not assessable.

V DISCUSSION AND CONCLUSIONS

Advection varies considerably throughout the year and an attempt was made to correlate this variation with known currents, horizontal temperature gradients, and winds. The results were disappointing. While advection reaches a peak in April and is also quite high in August, the scanty information on currents and temperature gradients and winds does not provide corroborating evidence. This conclusion does not rule out the possibility of such a correlation and it is suspected that denser information would show a relationship.

The errors in the heat budget analysis can be large, as shown in Table 5. During one period, the possible errors from inaccurate data used in computing Q_e, Q_h, and Q_b total 40% of the terms themselves. These errors, combined with a five percent error in Q_s, could reverse the sign of Q_v in some instances. Moreover, there are other sources of error in the analysis. The empirical formulae are not exact, nor is some of the methodology such as application of Chesapeake Light meteorological data to the entire study area.

It does appear, however, that there is a strong tendency for errors to cancel. This is especially true of observational errors where high readings will be offset by low ones as a result of the rounding-off process. Additionally, the observers were changed frequently, thus reducing observational bias.

Because of the magnitude of possible errors, the agreement of calculated and observed advection could be coincidental. To determine advection accurately and positively would require more accurate data collected at more frequent intervals at stations spaced closer together as well as better information on water movement in this area.

APPENDIX A

Error Computations

Errors in the various computed terms of the heat budget depend on the size of the meteorological parameters as well as the accuracy and precision of measurements. For this reason it is not proper to determine the worst possible error of any situation and apply it to all of the computations. Rather, it is more appropriate to determine the actual limits for each observation and sum the individual errors to obtain totals for the periods.

In compliance with the above, a FORTRAN IV computer program was written to calculate the heat budget terms for each meteorological observation in all possible error situations. The program then determined the maximum and minimum values of the terms which were summed and averaged to obtain the values given in Table 5.

In the case of Q_e, there are four independent variables - T_s, T_d, V, and RH. Each of these parameters can contain either negative, zero, or positive errors for a total of $(3)^4$ or 81 possible combinations. Q_b and Q_h have $(3)^3$ or 27 possible values since they are functions of three variables.

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